(TITLE UNCLASSIFIED) REUSABLE SUBSYSTEMS DESIGN/ANALYSIS STUDY

Vol I – Management Study Summary

L. L. Morgan

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AFRPL-TR-69-210
Vol I

(TITLE UNCLASSIFIED)
REUSABLE SUBSYSTEMS DESIGN/ANALYSIS STUDY

Vol I – Management Study Summary

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Lockheed Missiles & Space Company

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Air Force Rocket Propulsion Laboratory
Air Force Systems Command
Edwards Air Force Base, California

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Vol I

FOREWORD

The study summarized in this presentation was conducted by Lockheed Missiles & Space Company (LMSC) for the Air Force Rocket Propulsion Laboratory, Edwards, California, under contract F04611-69-C-0041. The study was under the technical direction of Mr. David T. Clift, Propulsion Subsystems Branch, Liquid Rocket Division, and Lt. George T. Reed, Analysis and Applications Branch, Liquid Rocket Division. The study technical effort has been conducted between the period from December 1968 to July 1969.

The study report is published in the following four volumes:

Volume I – Management Study Summary
Volume II – Technical Study Report
Volume III – Supplemental Data (Appendixes)
Volume IV – Special Supplemental Data

NOTE: Because of its size, Volume II is bound in two separate books: Part A contains Sections 1 through 5; Part B contains Sections 6 through 9. Both Part A and Part B contain a full table of contents, for the convenience of the reader.

Classified information has been extracted from those documents marked with an asterisk in Section 9, Volume II, Part B (References).

Major contributors of the study were as follows:

L. L Morgan – Study Manager
R. L. Gorman – Component Engineering
H. L. Jensen – Subsystem Engineering
R. F. Hausman – Accessibility and Subsystem Tradeoff Studies
H. K. Burbridge – Reliability Studies
C. V. Hopkins – Advanced Technology Programs
K. Urbach – Subsystems Checkout
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This technical report has been reviewed and is approved.

David T. Clift
AFRPL Project Engineer

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ABSTRACT

(U) This study was performed for the Air Force Rocket Propulsion Laboratory with the principal objectives of (1) determining the propulsion subsystem requirements for reusable launch vehicles and spacecraft, (2) determining the suitability of existing expandable propulsion subsystem technology and components for reusable applications, and (3) recommending subsystem component and design approaches which are best suited to manned reusable vehicles. The effort was limited to the analysis and evaluation of liquid rocket propulsion subsystems. Rocket engines were not examined study.

(U) Baseline vehicles were established by updating designs from previous studies. The selected vehicles consisted of three categories: (1) Reusable Space Launch Vehicles, (2) Cryogenic Spacecraft, (3) Storable Spacecraft. Two reference missions were established for each type of baseline vehicle, and designs were adjusted for each.

(U) The vehicle designs were extended to include the propulsion subsystems necessary for accomplishment of the agreed upon reference missions. The depth of these design definitions were sufficient to provide a basis for subsequent tasks. Certain particular problems related to reusable vehicles were examined, such as thermal analyses, re-entry hazards, design allowances, passivation hazards, and propellant specifications.

(U) Specific requirements were established for all of the propulsion subsystems for each of the reference vehicles, including total active and inactive life, required component cycles, acceptable propellant leakage, and acceleration loading. Evaluations were made of the availability of existing hardware to satisfy the subsystem and component requirements. Investigations were performed of the component replacement requirements and the overall effects on the probability of failure of various subsystems.

(U) Subsystem tradeoff evaluations were accomplished by displaying the various advantages and disadvantages of the subsystems in order that selection of particular components and designs could be completed. Reusable propulsion subsystem technology and component requirements derived throughout the study were translated into recommendations for specific exploratory development programs. Relative priorities have been established for the programs.

(U) The study resulted in the general conclusion that the current approaches to subsystem and component design are satisfactory for reusable propulsion subsystems, and suitable subsystems may be designed and operated using existing hardware, with the confidence that a number of flights may be completed within the lifetime of the com components.

(U) The technology program recommendations were directed, for the most part, at the accomplishment of specific objectives (such as the development of thermal protection systems, integrated attitude control systems, etc.), or at more general programs contributing to needed technology (such as fracture mechanics, leakage detection, etc.).

Section 1
INTRODUCTION (U)

(U) Reusable space transportation systems may be operational within the next 5 to 10 years. During the period of performance of this study, interest in industry and government has increased very significantly. The results of this study cover many of the aspects of reusable subsystems and will serve as a basis for determination of many of the future technology requirements. The initiation of this study by AFRPL was extremely timely, in view of the recent increased activities in reusable space transportation systems.

(U) The growth of interest and activities in reusable space transportation systems during the period of this study was so rapid that even the "baseline" designs established as study references have become outdated. However, the conclusions regarding components and subsystems, operational modes, and required technology programs are applicable even to the largest reusable space transportation systems currently being investigated at the time of this report.

(U) The major output of the Reusable Subsystems Design/Analysis Study was the Advanced Technology programs recommendations, which were considered to be requirements and/or desirable inputs to future reusable vehicle programs. Throughout the study, an attempt was made to identify the Advanced Technology requirements for each of the subsystems of the reusable vehicle at the time that the evaluations were being performed. This approach increased the effectiveness of the assessment of the technology requirements.

1.1 OBJECTIVES AND SCOPE (U)

(U) The principal objectives of this study were as follows:

- To determine the propulsion subsystem requirements for reusable launch vehicles and spacecraft (as applicable to selected reference designs)

- To determine the suitability of existing expendable propulsion subsystem technology and components for reusable applications
- To recommend subsystem components and design approaches which are best suited to manned reusable vehicles.

(U) The effort was limited to the analysis and evaluation of liquid rocket propulsion subsystems and the application of these to reusable launch vehicles and spacecraft. Rocket engines were not examined in the study.

(U) The steps in accomplishing the study are shown in Figure 1-1. Reference vehicles were established by updating previous designs. The designs of the propulsion subsystems of these reference vehicles were extended to more depth, as necessary, and analyses were conducted. Requirements for components and subsystems were established. Existing components were examined in view of the requirements. Subsystem tradeoffs were performed to present the advantages and disadvantages of the systems. All steps of the study effort were examined to determine the advanced technology requirements.

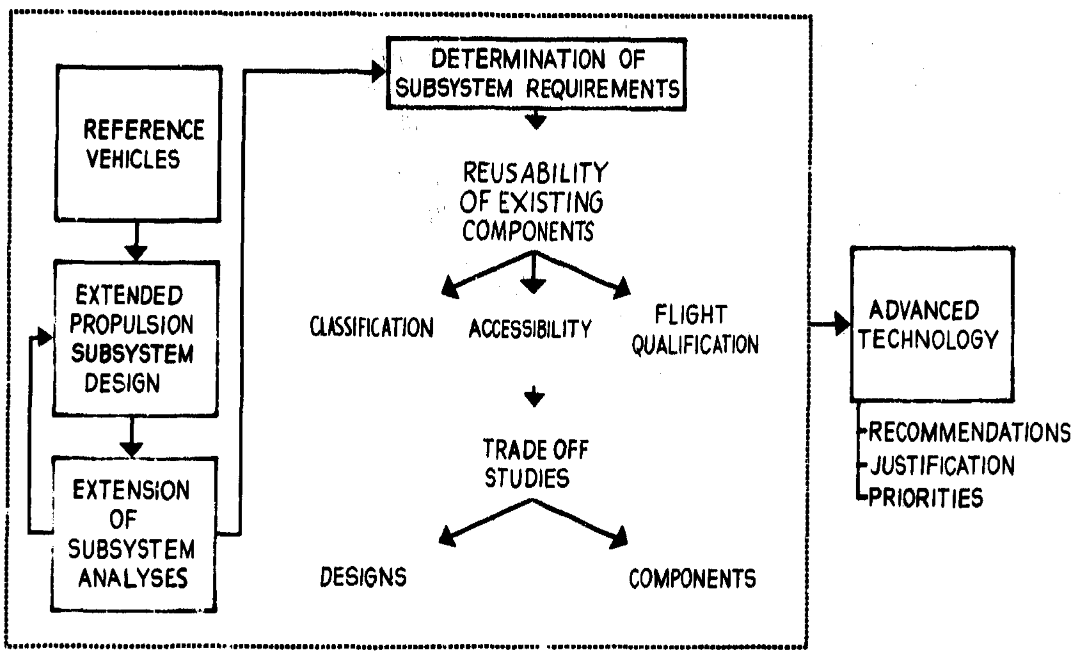


Figure 1-1 Overall Study Approach (U)

1.2 STUDY TASK DIVISION (U)

(U) The Study was divided into seven major tasks:

TASK 1 – SELECTION OF VEHICLES AND MISSIONS (U)

(U) The objective of Task 1 – Vehicle Selection, was to select three specific vehicle configurations to be utilized in conducting the analyses. These configurations are to provide the basis for extension of the designs in Task 2 and detailed analyses in Task 3.

(C) The technical requirements of the contract stated that the selected vehicles fit into three categories:

(1) Reusable Space Launch Vehicle, LO_2/LH_2
(2) Cryogenic Spacecraft, LF_2/LH_2
(3) Storable Spacecraft, N_2O_4/50-50

(C) These baseline vehicles represented application of the liquid rocket engines being considered by AFRPL in existing advanced development programs or contemplated programs.

TASK 2 – VEHICLE DESIGN EXTENSIONS AND SUBSYSTEM ANALYSIS (U)

(U) The vehicle designs were extended to include the propulsion subsystems necessary for accomplishment of the agreed upon reference missions. The depth of these design definitions was sufficient to provide a basis for the evaluations in subsequent tasks. This task required maximum use of existing data and related experience. The output of this task includes very little relative to selected components.

TASK 3 – EXTENSION OF SUBSYSTEM ANALYSES (U)

(U) The purpose of this task was to extend the analyses of the designs resulting from Task 2, to examine certain particular problems related to reusability, and to provide a broader basis for establishment of subsystem requirements.

(C) Specific problems which were examined included: thermal analyses, reentry hazards, design allowances, passivation hazards, and propellant specifications.

TASK 4 – DETERMINATION OF SUBSYSTEM REQUIREMENTS (U)

(U) The objective of this task was to determine the specific requirements for all of the propulsion subsystems for each of the three vehicle configurations. The major requirements examined in the task included:

- Total active and inactive life
- Required number of component cycles
- Acceptable propellant leakage rates
- Acceleration loading (g vectors)

TASK 5 – REUSABILITY OF EXISTING HARDWARE (U)

(U) The objective of this task was to determine the availability of existing hardware to satisfy the subsystem and component requirements established for the vehicles. Several alternate components were considered for each of the applications, with the objective of determining whether the requirements and reusable aspects were satisfied rather than the selection of particular components for the application.

(U) An important activity in this task, and in Task 6, was the evaluation of the component replacement requirements and the overall effect on the probability of failure (reliability) of the various subsystems. These investigations reflected significantly upon the predictability of the subsystems. Investigations were accomplished through the use of an advanced computer program.

TASK 6 – SUBSYSTEM TRADEOFF EVALUATIONS (U)

(U) The objective of this task was to complete the selection of particular components and designs from the alternatives. The subsystem tradeoff evaluations were performed by displaying the various advantages and disadvantages of the subsystems in order that selections could be made. Considerable use was made of the SETA II outputs, which

(U) provided information on the number of component replacements and the relative probabilities of failure.

TASK 7 – ADVANCED TECHNOLOGY (U)

(U) This task translated the reusable propulsion system technology and component requirements derived throughout the study into recommendations for specific exploratory development programs. Justifications are provided for the programs, and included in these are a review of past investigations. Relative priorities have been established for the programs.

1.3 GENERAL CONCLUSIONS (U)

(U) At the beginning of the study, there was considerable doubt regarding the applicability of existing component approaches to reusable vehicles. Also, it was apparent from previous studies that the major influencing factors had not been given serious consideration. As a result of this study, it was concluded that major changes in approach were not necessary to obtain satisfactory reusable systems.

(C) The study resulted in the general conclusion that the current approaches to subsystem and component design are satisfactory for reusable propulsion subsystems. It was determined in the study that insufficient component lifetime data are available at this time to determine accurately the performance of subsystems. However, examination and extrapolation of existing data resulted in the conclusion that suitable subsystems may be designed and operated using existing hardware, with the confidence that a number of flights may be completed within the lifetime of the components.

(U) An important conclusion of the study was that "wearout" as such should not be a factor in reusable vehicles. Components must be replaced before wearout effects increase the failure rates of components; otherwise, control of reliability is very difficult.

(C) The subsystems of the Reusable Launch Vehicle (Space Shuttle) were found to be very dependent upon the characteristics of the engine, as these characteristics will be defined in a future development program. The feasibility, cost, and schedules associated with

(C) engine development will be the ultimate determining factors in the selection of the major subsystems for the Space Shuttle.

(U) The study did not result in the recommendation for major investigations to determine the lifetime and reusability of a large number of component types. It was generally concluded after examination of the status of existing components that little activity in terms of "general technology" would be required, and extensive testing programs would be more costly than the results warranted.

(U) The technology program recommendations were directed, for the most part, at the accomplishment of specific objectives (such as the development of thermal protection systems, integrated attitude control systems, etc.), or at more general programs contributing to needed technology (such as fracture mechanics, leakage detection, etc.).

Section 2

SELECTION OF VEHICLES AND MISSIONS AND EXTENSION OF VEHICLE DESIGNS AND ANALYSES (U)

(C) As a consequence of previous Lockheed-sponsored and Government-sponsored work, Lockheed recommended for selection three reusable space transportation systems for examination and approval by the Air Force Rocket Propulsion Laboratory, and two missions were selected for each of these through joint agreements. These baseline vehicles represented application of the liquid rocket engines being considered by AFRPL in existing advanced development programs or contemplated programs.

- Project 1: N_2O_4/50-50 Propellants – Similar to the Aerojet General Corp. MIST engine
- Project 2: LO_2/LH_2 Propellants – Pratt & Whitney XLR-129-P-1 engine
- Project 3: LF_2/LH_2 Propellants – Rocketdyne AMPS engine

(U) Necessarily, the reusable vehicles selected in January 1969 were representative of the principal advanced concepts at that time. Recently, there has been considerable evolution in the Space Shuttle vehicle designs. However, the results of this study are still generally applicable to the Space Shuttle systems, since similarity in the requirements exist.

2.1 SELECTED VEHICLES (U)

(C) The specific Reusable Launch Vehicle (Space Shuttle) was represented by the Lockheed Space Shuttle stage-and-one-half-to-orbit multimission launch vehicle, shown in Figure 2-1. Space Shuttle has a payload capability of up to 26,000 lb in low earth orbit, a crew/passenger capability of two to nine men, and an orbit staytime of up to 30 days.

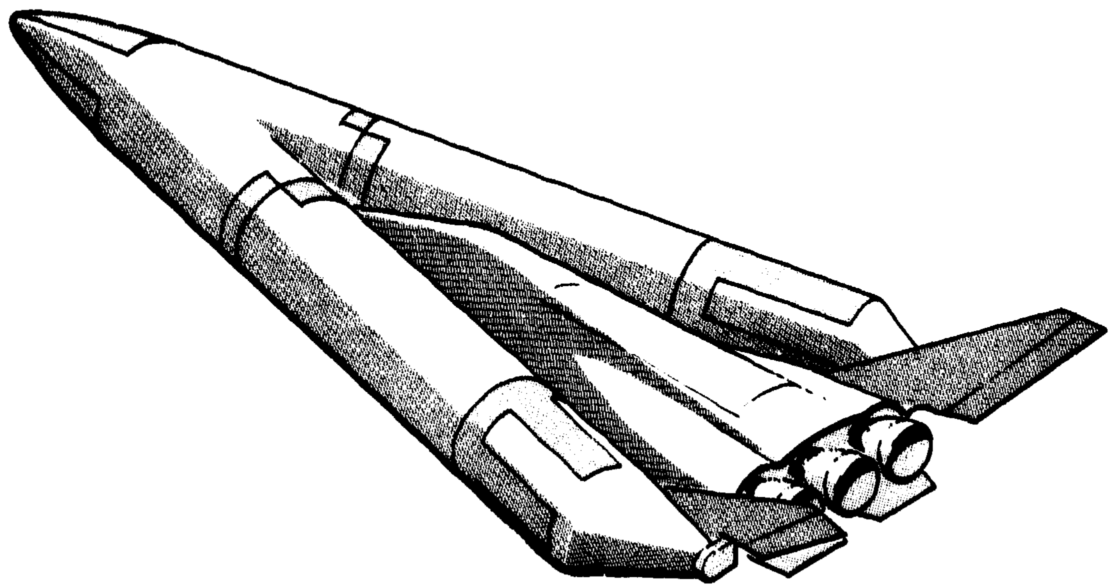


Figure 2-1 Selected Reusable Launch Vehicle (U)

(C) Two versions of this vehicle were utilized, for two different missions. The baseline design configuration utilized three 350,000-lb-thrust, AFRPL Project 2 engines (XLR-129-P-1).

(C) The reusable spacecraft used with the LF_2/LH_2 propellants and the N_2O_4/50-50 propellants was based upon the FDL-5 vehicle designed by Lockheed (Figure 2-2). Reusable spacecraft with high L/D are typically boosted to orbit by the Titan III vehicle.

(C) Four versions of the FDL-5 configuration were required to satisfy the requirements of the missions:

- Cryogenic LF_2/LH_2: 3 men – 30 days
2 men – 14 days
- Storable N_2O_4/50-50: 3 men – 30 days
Unmanned – 180 days

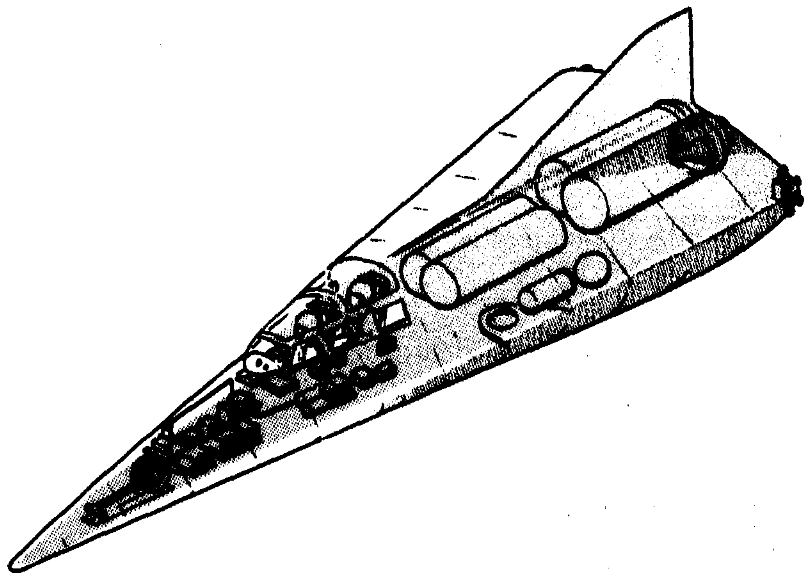


Figure 2-2 FDL-5 Vehicle Configuration (Cryogenic and Storable Spacecraft) (C)

(C) The cryogenic versions utilize the 30,000-lb-thrust, AFRPL Project 3 engine (AMPS). The storable versions are assumed to utilize the 30,000-lb-thrust, AFRPL Project 1 advanced storable engine.

2.2 SELECTED MISSIONS (U)

(C) A total of five missions were selected to be performed by the reusable vehicles, as presented in Table 2-1. These included two for the Space Shuttle stage-and-one-half-to-orbit launch vehicle, one mission specifically for the LF_2/LH_2 cryogenic spacecraft, one common mission for the LF_2/LH_2 cryogenic spacecraft and the N_2O_4/50-50 storable spacecraft, and one mission specifically for the N_2O_2/50-50 storable spacecraft. Therefore, two versions of each of the three vehicles were examined to provide a basis for determination of subsystem requirements.

Table 2-1

SELECTED MISSIONS
(CONFIDENTIAL)

SPACE SHUTTLE (REUSABLE LAUNCH VEHICLE)

- Mission I – Logistics Resupply – 4 Days
- Mission II – Orbital Experiment – 30 Days

FDL-5 LF_2/LH_2 PROPELLANTS

- Mission III – Military – 30 Days
- Mission IV – Inspection – 14 Days

FDL-5 N_2O_4/50-50 PROPELLANTS

- Mission III – Military – 30 Days
- Mission V – Inspection – 180 Days

2.2.1 Mission I Logistics Resupply (C)

(C) Requirements for this mission were developed from an analysis of the resupply and crew rotational needs of a earth-orbiting space station. The Space Shuttle launches into a circular parking orbit at an altitude of 100 nm. Ascent staging and drop tank jettison occur when the drop tank propellant is expended. A waiting period of approximately 4 hours in the parking orbit is allowed for phasing. After phasing in the parking orbit, the transfer to 260 nm requires approximately 45 minutes, and 1.5-degree plane change is effected. A gross rendezvous with a 20 nm separation is accomplished. The terminal phase ends at about 1,000 ft from the target vehicle, where the docking procedures, using secondary propulsion, would begin. After the orbital resupply operations, entry would be initiated by the application of the retro impulse with the main propulsion system.

2.2.2 Mission II Orbital Experiment (U)

(C) This mission is similar to Mission I with regard to ascent, deorbit, and entry. The staytime in orbit is extended to 30 days. The vehicle performs three transfers and two circularizations. The mission requires perigee freeze, which is performed by the secondary propulsion system, combining this with drag make-up.

2.2.3 Mission III Military (C)

(C) This is an orbital mission involving plane change only, without synergetic maneuvers. The mission velocities were based upon the maximum obtainable from reference Lockheed LF_2/LH_2 spacecraft, and this velocity was used to size the N_2O_4/50-50 spacecraft.

(C) The spacecraft performs two transfers, two circularizations, a plane change, and a deorbit. Perigee freeze by the secondary propulsion system is required.

2.2.4 Mission IV Inspection (C)

(C) Mission IV involves both orbital maneuvers and plane changes. The plane changes are accomplished by both pure impulsive and synergetic maneuvers. The velocity capabilities are based upon the maximum propellant loadings that can be accomplished in the reference vehicle envelopes.

(C) It was assumed for the study that the inspection mission included two inspections of evasive targets. Environments were established for the synergetic plane change maneuvers, combining aerodynamic and thrust maneuvering.

2.2.5 Mission V Inspection (C)

(C) This mission is similar to Mission IV-Inspection, with the exception that the total mission time is 180 days, and the vehicle is unmanned. The velocity capability is based on the maximum propellant loading possible within the vehicle envelope. In order to provide commonality with Mission IV, two inspections of evasive targets were assumed.

(U) This mission was included to allow consideration of problems that might be related to long duration missions.

2.3 EXTENSION OF VEHICLE DESIGNS AND ANALYSES (U)

(U) The vehicle designs were extended to include the propulsion subsystems necessary for accomplishment of the agreed-upon reference missions. The depth of these design definitions was sufficient to provide a basis for the following:

- Extended subsystem analyses, including examination of special problems
- Establishment of subsystem design, development, and operational requirements
- Evaluation of existing hardware to determine its ability to satisfy these requirements
- Subsystem tradeoff studies for selection of reusable components and designs.

(U) The vehicle designs were extended in the areas of:

- Propellant tankage
- Tank support
- Propellant orientation
- Feedline systems
- Schematics
- Subsystem analyses
- Thermal protection

2.3.1 Propellant Tankage (U)

(U) Several propellant tank arrangements were examined for each of the vehicles, and some of the principal approaches are indicated in Figure 2-3. The purpose of these investigations was to uncover factors affecting reusability, problems associated with feedlines, etc.

(U) The Space Shuttle tank designs shown here have proved to be generally applicable to a wide family of vehicles. A separate tank for deorbit retro propellant or maneuver/retro propellant is desirable.

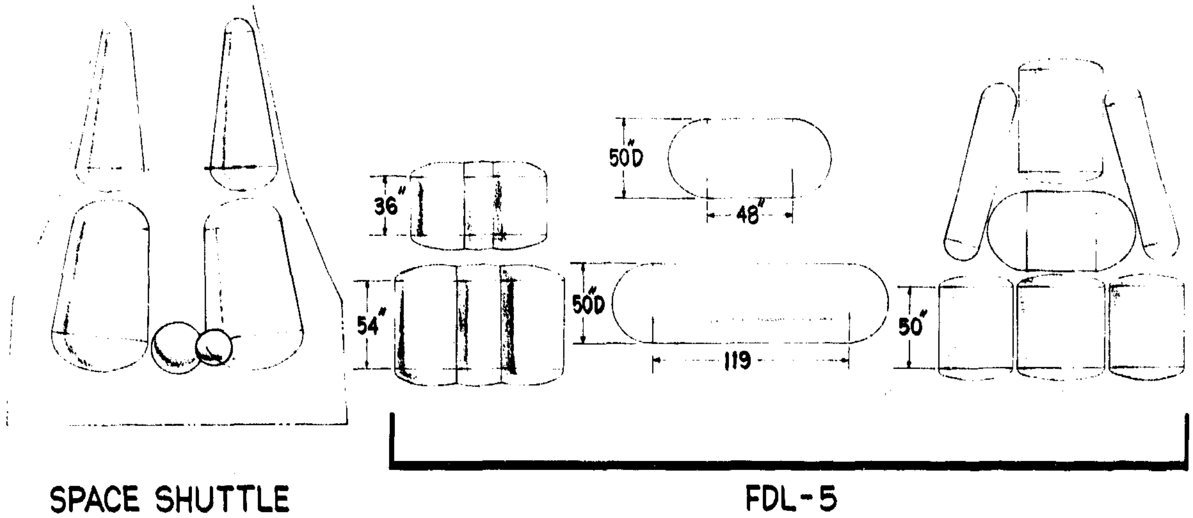


Figure 2-3 Reusable Tankage Approaches (U)

(U) To obtain information for the required design allowables and the reusability of tankage to be performed in Task 3, stress level and weight data were produced for several typical tanks. The tank weights were relatively low.

(U) Two general conclusions resulted from the Task 3 subsequent effort:

- The required number of pressure cycles is too low to constitute a serious influence on the tankage reusability.
- The sustained loading of the tanks for the required time periods is the major factor influencing fracture.

(U) Two difficulties were encountered in obtaining definitive results from the evaluations:

- The material thicknesses are low, which limits the applicability of fracture analytical methods.
- Limited data are available regarding threshold stress intensity factors for crack growth in the various propellant environments.

(U) The "leak before break" criteria expressed mathematically were applied to the 2219 aluminum alloy of 0.063, 0.100, and 0.150 inch thicknesses. The data indicate that "leak before break" would occur for approximately 0.060-in. thick 2219-T87 aluminum at -423°F. Similarly, "leak before break" should occur for the 2219-T851 aluminum weldments for thicknesses up to 0.150 inch at -320° and 155°F.

2.3.2 Propellant Orientation (U)

(U) Propellant orientation was considered in all phases of the study. The results of these evaluations indicate that surface tension devices are desirable for orientation of the propellant for orbit starts.

2.3.3 Pressurization (U)

(U) The complexity of the pressurization subsystems make them important considerations in reusable vehicles. Also, these systems have a significant impact upon the engine design and development.

(U) Some of the more significant pressurization subsystems are summarized in Table 2-2. While there are wide differences in the applicability and operating approaches the weight differences between the systems are not excessive.

(U) Autogenous pressurization is defined as the Space Shuttle system that uses only engine bleed for both prepressurization and pressurization. This requires a "bootstrap" capability within the engine. It was determined that the required times for prepressurization by the autogenous method are acceptable. They are on the order of less than 10 seconds for engine source pressures of 100 psia, dropping to less than 5 seconds for engine source pressures of 200 psia.

(C) The other Space Shuttle pressurization subsystem receiving considerable attention in the study was the other extreme, the system employing helium prepressurization and helium pressurization of the LO_2 tank, and GH_2 engine bleed for pressurization of the LH_2 tank.

Table 2-2

PRESSURIZATION RESULTS SUMMARY (U)
(CONFIDENTIAL)

Vehicle	Prepressurization		Pressurization		System	He (lb)	Residuals		System Weight (lb)	Total Penalty
	Oxid	Fuel	Oxid	Fuel			Oxid (lb)	Fuel (lb)		
Space Shuttle	He	He	He	H_2	Cold He + H. E.	65	182	242	554	1043
	He	He	He	H_2	Amb. He	68	182	242	977	1469
	He	He	O_2	H_2	Cold He + H. E.	47	266	242	514	1069
	He	He	O_2	H_2	Amb. He	51	266	242	818	1377
	O_2	H_2	O_2	H_2	Engine Bleed		401	242	334	977
LF_2/LH_2 Mission III FDL-5	He	He	He	H_2	Instant Start	67	36	29	146	277
	He	He	He	H_2	Normal Start	16	21	29	170	236
Mission III N_2O_4/50-50	He	He	He	He		8			96	104

(C) The "instant start" pressurization subsystem for the LF_2/LH_2 FDL-5 is the system being examined for AMPS, in which the tanks are maintained for instant start at all times. The "normal start" subsystem involves a prepressurization step with heated helium.

2.3.4 Thermal Protection (U)

(U) An advantage of using the large Space Shuttle reusable tanks for ascent only is apparent in the thermal protection system. If no orbital storage of propellants in the ascent tanks is necessary, foam insulation can be used, which is less costly and is easier to repair and maintain. Multilayer insulation is required for the maneuver/retro tanks. Since the Space Shuttle must start on the ground, it is necessary that the propellant conditions be held within desirable limits on the ground. Since it is also desirable to keep the propellant vapor pressures low, the tanks are vented until the last few minutes; there is little pressure suppression to prevent gas formation in the feedlines and manifolds; and high recirculation rates are required to limit the temperature rise if vacuum jacketed feedlines are not employed.

(C) Since the propellant tanks are so small in the LF_2/LH_2 FDL-5, vacuum jacketing of the tanks is not out of the question. This would add considerably to the flexibility of such a system. Vacuum jacketing of the LF_2 tank would increase the weight by approximately 300 lb.

(U) The multilayer insulations on all of the cryogenic vehicles must be purged during launch and entry. This is to prevent the condensation of moisture and air. The insulation lifetime will also be increased. A "breathing" type of purge system is required for the entry phase.

2.3.5 Attitude Control (U)

(U) The attitude control thruster locations assumed for the study are shown in Figure 2-4. The indicated thrust levels are adequate for the maneuver rate requirements established for the study.

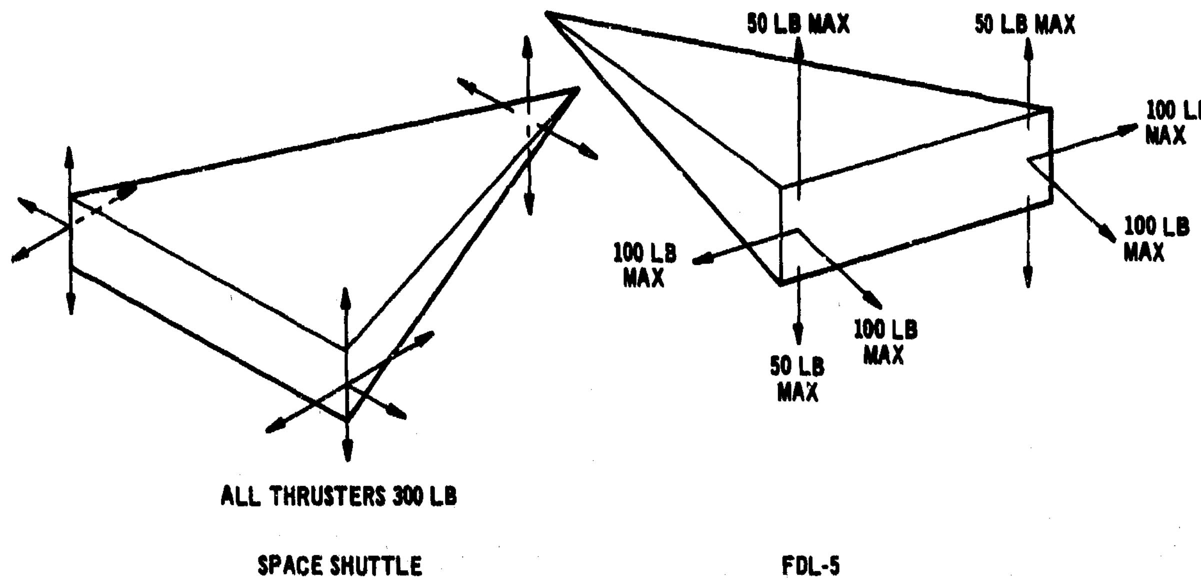


Figure 2-4 Attitude Control Thruster Locations (U)

2.3.6 Reentry Considerations (U)

(U) During the entry phase of the mission, the atmosphere containing moisture will enter the propellant bay cavity during descent, unless excluded by purging. An analysis was made to determine the magnitude of this effect. It was found that only 0.2 lb of water vapor will condense per 100 cu ft of propellant bay of the Space Shuttle. However, if a differential pressure of 0.03 psia is maintained to exclude the atmosphere by purging, the weight penalty will be significant unless very tight, mobile sealing is provided.

(C) It was concluded that propellant dumping can be most logically performed through the engine. The propellants must be dumped in liquid flow. The engine vents of the Project 2 engine would allow dumping of residual propellants in less than 500 seconds, which is acceptable since the time from deorbit to entry is approximately 1200 seconds.

(U) An evaluation was also made to determine tank pressure rises through a normal entry, landing, and hook-up to ground support equipment if the propellant residuals were not dumped from the ascent propellant tanks.

2.3.7 Passivation Investigations (C)

(C) The investigation of the passivation of LF_2 subsystems tended to indicate that repassivation is necessary as a preflight operation. The fluorine fill, drain, and vent system would be the primary means of repassivation.

(U) Repassivation of disconnects is of considerable concern since these will be exposed to the atmosphere during launch and entry.

(U) In a reusable vehicle, the importance of the purity of gases, both for pressurization and ground support, is emphasized. Accumulation of moisture contamination in helium pressurization bottles, as an example, can introduce a serious hazard.

Section 3

REQUIREMENTS, COMPONENT EXAMINATIONS, AND SUBSYSTEM TRADEOFFS (U)

(U) In order to allow examination of existing hardware for application to the reusable subsystems, and to allow the tradeoff studies to proceed, it was necessary to establish the subsystem requirements in terms of the application of these in the vehicles and missions under consideration.

(U) The determination of the applicability of existing hardware for expendable vehicles to requirements in the reusable vehicles was given a major emphasis in this study. Particular attention was given to the identification of candidate components for which adequate performance information was available as the result of actual usage on current or past propulsion subsystems. This effort required the participation of manufacturers and suppliers of aerospace components. The attention given by these companies to this study, and the responses received contributed significantly to the results. A considerable quantity of technical effort and assistance was contributed by these manufacturers and suppliers.

(U) Comparisons were made of the subsystems to determine the most logical selections based upon the available information. The selection of the subsystems is naturally very dependent upon the conditions and design features of the reference vehicles. However, an attempt was made to generalize the conclusions, and to provide suitable alternate selections where possible. Also, in some instances, the choices are influenced by existing technologies and available data. Advances in technology could alter the decisions.

3.1 DETERMINATION OF SUBSYSTEM REQUIREMENTS (U)

(U) All of the steps in the operational cycle of the reusable vehicles were considered in the establishment of the subsystem requirements. The steps considered are presented

in Figure 3-1 and from these the total active and inactive life requirements, the required number of component cycles, and the system checkout requirements were determined.

3.1.1 Main Propulsion Subsystem Cycle Requirements (U)

(U) The required number of operations during flight of the primary propulsion systems is presented in Table 3-1. These cycles do not include checkout.

(U) It was necessary to examine each component in the subsystems to determine the number of cycles for each so that the predictability analyses described later could be performed.

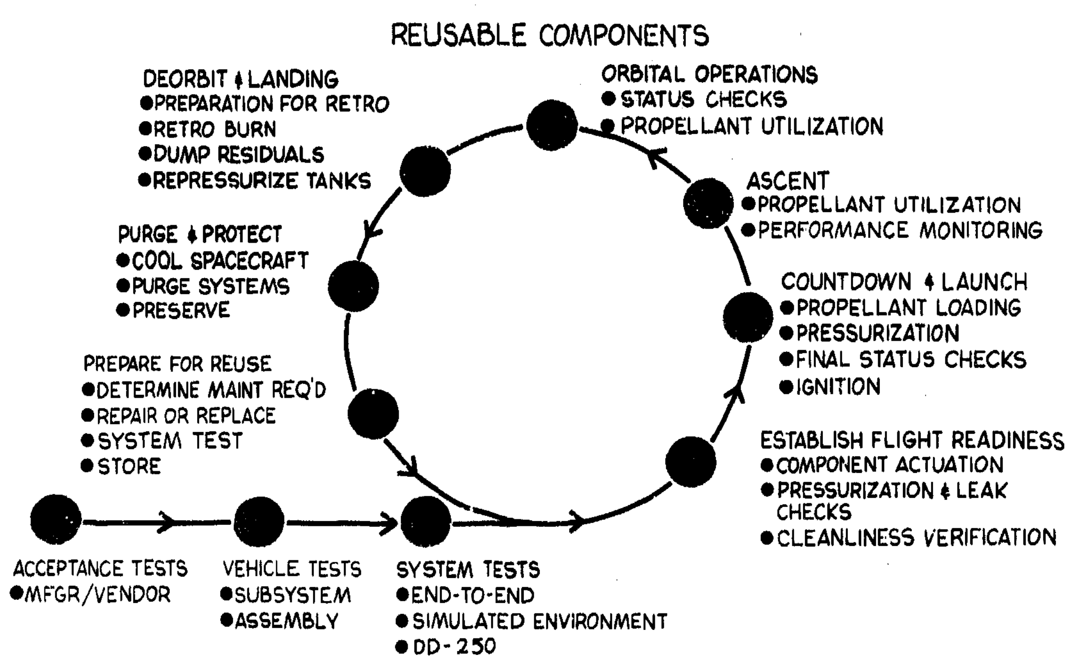


Figure 3-1 Reusable Vehicle Operational Cycle (C)

Table 3-1

PROPULSION SUBSYSTEM CYCLE REQUIREMENTS (U)
(CONFIDENTIAL)

	Propellant Feed		Prepressure		Pressurized		TCU Vent	Relief Valve	
	Oxidizer	Fuel	Oxidizer	Fuel	Oxidizer	Fuel	(GH_2)	Oxidizer	Fuel
Space Shuttle									
Mission I	4	4	4	4	4	4	1	1	1
Mission II	6	6	5	5	6	6	3	2	2
LF_2/LH_2 FDL-5									
Mission III	6	6	5	10	6	6	34	1	1
Mission IV	27	27	3	7	27	27	16	1	1
N_2O_4/50-50 FDL-5									
Mission III	6	6	–	–	6	6	–	1	1
Mission V	27	27	–	–	27	27	–	1	1

3.1.2 Attitude Control Cycle Requirements (U)

(U) An extensive investigation was made of the attitude control subsystems because they are particularily sensitive to the component cycles. An important consideration in the mission requirements was the relatively long orbit parking, and subsequently, the limit cycling. The minimum engine impulse bit is very important in the propellant consumption and the number of cycles required.

(U) The number of required attitude control cycles per thruster per mission are presented in Table 3-2 for two minimum impulse bits. For the FDL-5 spacecraft, minimum impulse bits A and B consist of:

Group A: All 100-lb thrusters – 1.5 lb-sec
All 50-lb thrusters – 0.75 lb-sec

Group B: All 100-lb thrusters – 0.5 lb-sec
All 50-lb thrusters – 0.3 lb-sec

Table 3-2

ATTITUDE CONTROL CYCLE REQUIREMENTS (U)

(CONFIDENTIAL)

Vehicle & Mission	Minimum Impulse Bit	Pitch & Roll	Yaw	Translation
Space Shuttle Mission I	3	2,300	610	4
	1.5	1,240	330	4
Space Shuttle Mission II	3	34,300	13,500	164
	1.5	19,900	7,600	164
LF_2/LH_2 FDL-5, Mission III	(A)	17,000	7,300	382
	(B)	12,000	5,100	382
LF_2/LH_2 FDL-5, Mission IV	(A)	4,350	1,920	14
	(B)	3,750	1,600	14
N_2O_4/50-50 FDL-5, Mission III	(A)	15,300	12,000	164
	(B)	11,100	4,700	164
N_2O_4/50-50 FLD-5, Mission V	(A)	45,700	21,600	92
	(B)	36,500	23,000	92

3.1.3 Checkout Cycles (U)

(U) As previously indicated, the number of checkout cycles was determined for each of the components. Experience from previous programs, such as Saturn V and Agena, was reviewed in determining the non-recurring and recurring checkout requirements.

3.1.4 Allowable Leakage Requirements (U)

(U) In order to determine the leakage requirements, analyses were made of the various missions with regard to the effects of leakage on the overpressurization of the propellant tanks and on the loss of helium gas/propellant gases from the tanks. In evaluating the overpressurization of propellant tanks, it is only necessary to consider helium leakage. Also, in the leakage of gases from propellant tanks, the important consideration, other than the fluorine hazard, is the loss of helium. Propellant losses are negligible.

(U) In performing these analyses, estimates must be made of the ullage gas composition throughout the mission.

(U) The estimated allowable leakages presented in Table 3-3 are based upon assumptions that:

- Leakage into the tanks over the entire mission does not result in a pressure rise of more than 2 psia
- Helium leakage from the tanks is less than 10 percent of the stored helium.

3.2 REUSABILITY OF EXISTING HARDWARE (U)

(U) The objective of this task was to determine the availability of existing hardware to satisfy the subsystem and component requirements established for the vehicles. The magnitude of the task makes reporting of the results difficult; by necessity some of the results must be reported in generalities.

(U) The requirements for each of the components in the subsystems under investigation were provided to suppliers of Saturn, Centaur, Apollo, Titan, Agena, etc., components for their examination, and direct contacts were made with the engineering personnel of most of the companies. Specifications, drawings, hardware, etc., were examined for applicability. Several alternate components were considered for each of the applications with the objective of determining whether the requirements and reusable aspects were satisfied rather than the selection of particular components for the application. Modifications were identified where possible. Also, in this data collection, reliability and lifetime data were obtained.

3.2.1 Reusable Launch Vehicle (Space Shuttle) (U)

(U) As previously discussed, some generalizations are necessary to summarize the trends resulting from the investigations. The comments presented in Table 3-4 relate to the Space Shuttle specifically examined in the study; however, these comments will generally apply to larger vehicles with a few exceptions, such as the size of feedline valves.

Table 3-3

ESTIMATED ALLOWABLE LEAKAGE RATES (U)

(CONFIDENTIAL)

Vehicle	Mission	Propellant Tank	Gas Leakage scc/min	
			GHe Into Tanks	Gas From Tanks
Space Shuttle	I	LO_2	600	600
		LH_2	6000	6000
		LO_2 Retro	3	25
		LH_2 Retro	25	300
	II	LO_2	80	100
		LH_2	1000	1200
		LO_2 Retro	3	3
		LH_2 Retro	4	50
FDL-5 (LF_2/LH_2)	III	LF_2	10	60
		LH_2	12	800
	IV	LF_2	100	100
		LH_2	80	2000
FDL-5 (N_2O_4/50-50)	III	N_2O_4	1	5
		50-50	1	1
	V	N_2O_4	1	5
		50-50	1	1

Table 3-4

SUMMARY OF COMPONENT AVAILABILITY FOR THE REUSABLE LAUNCH VEHICLE (C)
(CONFIDENTIAL)

Component Class	General Conclusions
Propellant Feed Valves	Suitable components are available with modifications. Gas leakages tend to be higher than desired. Actuators should be modified for cryogenic temperatures.
Vent and Relief Valves	Suitable components are available with modifications. Gas leakages tend to be higher than desired. Actuators should be modified for cryogenic temperatures.
Thermal Conditioning Units	Units with more capacity than those currently under development are required.
Liquid Line Quick Disconnects	If propellant crossfeed from drop tanks is used, larger disconnects are required. The units must have more predictable response. (Alternate combination of valves and line separators may be used.)
Vent Disconnects	If vents are connected from the drop tanks to the Reusable Launch Vehicle, these must have more predictable responses than existing disconnects. Components of compatible sizes are available.
Fill and Drain Disconnects	Larger diameters are desirable.
Pressurization Disconnects	If the drop tanks are to be pressurized from the Spacecraft, more predictable responses are necessary.
Pressurization Valves	If helium pressurization is used, valve leakages tend to be too high. Suitable sizes are available.
Pressurization Regulators	Suitable components available. Capacities of integral filters may have to be increased.
Pressure Switches	Lifetime extensions are required.
Pressure Transducers	Lifetime extensions are required.
Propellant Utilization	Vehicles would benefit from improved accuracies.
Liquid Level Devices	Lifetime extensions are needed.
Check Valves	Lifetime extensions are needed. This is particularly required for attitude control subsystems.
Attitude Control System Thrusters	Lifetime extensions are needed. Also, oxygen/hydrogen attitude control thrusters are required.

(U) It should be noted that with the exception of check valves, most of the valves and regulators have acceptable lifetimes based upon the lifetime estimates.

(U) In general, larger quick disconnects, which have a predictable response in flight, are required. This is contingent upon their use, since a combination of a valve and an explosive or mechanical line separator may be used in disconnecting from the drop tanks in flight. Larger fill and drain disconnects are desirable.

(U) "Instrumentation" type components generally need improved lifetimes.

3.2.2 Cryogenic Spacecraft (LF_2/LH_2) (C)

(C) Since liquid fluorine represents a relatively new technology with no flight vehicles currently in a development stage, the extent of component development to date in no way compares to the status of LO_2/LH_2 systems. A summary of previous investigations is presented in Figure 3-2.

(C) However, in the examination of the various existing cryogenic components, it was apparent that many of the features of later designs are applicable to LF_2 and modification for fluorine service would not be difficult.

(C) Since most of the LF_2 components exist as prototype or conceptual designs, most of the comments presented in Table 3-5, are based upon development of these into flight hardware or upon modification of existing hardware. An interesting factor in the LF_2/LH_2 stage is that few components actually contact fluorine in normal service. The pressurization system is entirely excluded with the exception of the check-valves, and possible contact with the regulator. "Instrumentation" in the fluorine tank receives considerable exposure, and this is combined with generally poor lifetime characteristics.

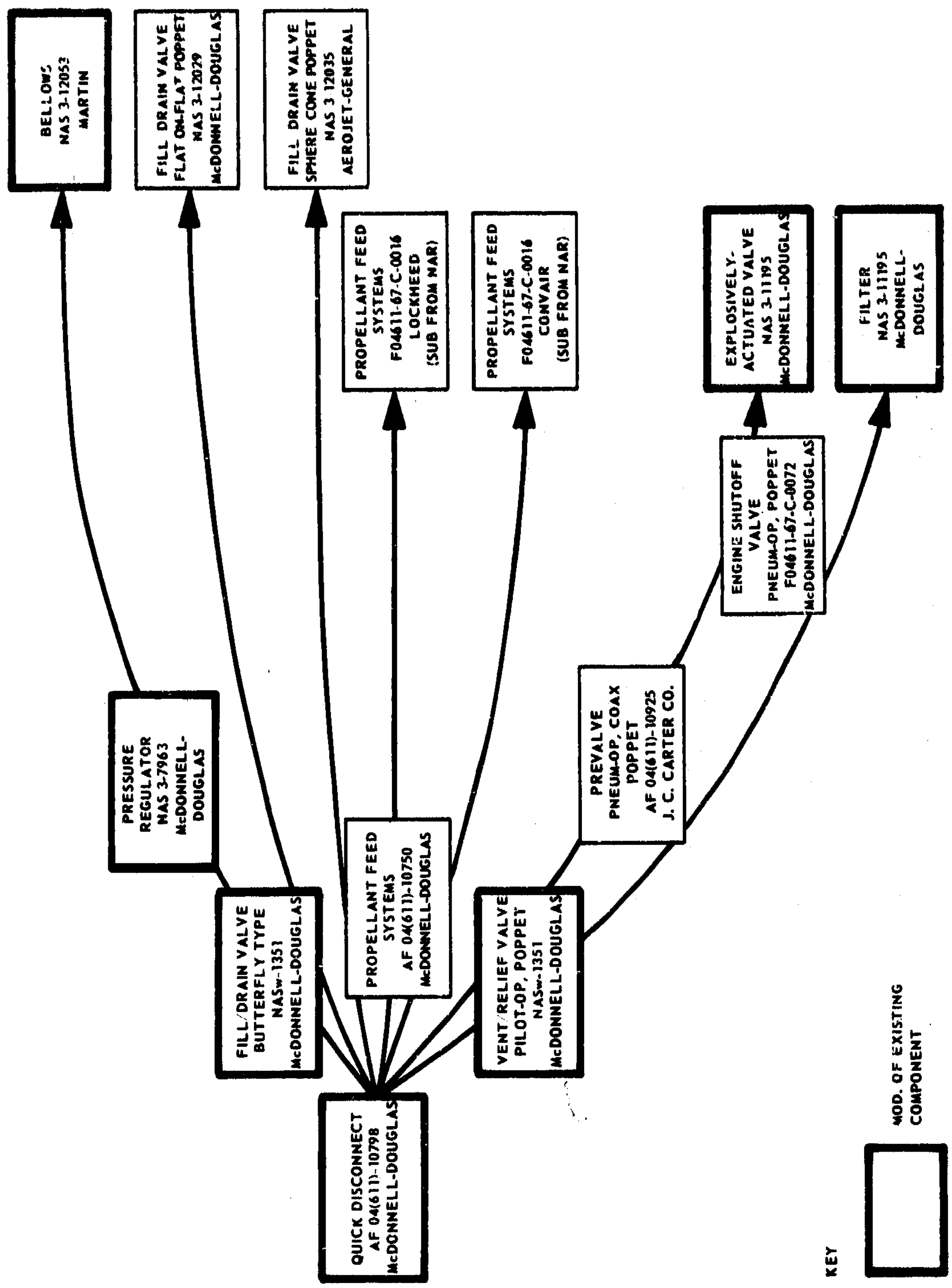


Figure 3-2 Previous LF_2 Subsystem and Component Developments (C)

Table 3-5

SUMMARY OF COMPONENT AVAILABILITY FOR THE CRYOGENIC SPACECRAFT (C)

(CONFIDENTIAL)

Component Class	General Conclusions
Liquid Valves	Suitable components are available for liquid hydrogen, with modifications. Previous fluorine valves indicate that suitable components can be developed.
Vent and Relief Valves	Suitable components are available for liquid hydrogen, with modifications. Previous valve investigations indicate components can be developed.
Thermal Conditioning Units	Required for liquid hydrogen only. Units of approximately the required size are under development.
Vent Disconnects	Suitable components are available for hydrogen. Fluorine component development has indicated solutions.
Fill and Drain Disconnects	Suitable components are available for hydrogen. Component development for fluorine possible.
Regulators	Suitable components available. Additional development work is necessary for fluorine-compatible regulators.
Pressurization Valves	Suitable components are available for both hydrogen and fluorine. Fluorine compatibility is not required.
Pressure Switches	Lifetime extensions are required. Additional development for fluorine compatibility is considered required.
Pressure Transducers	Lifetime extensions are required. Additional development for fluorine compatibility is considered required.
Check Valves	Lifetime extensions are required for hydrogen check valves. Fluorine compatible checkvalves development is necessary.
Propellant Utilization	Vehicles would benefit from improved accuracies.
Attitude Control Thrusters	Thrusters with extended lifetimes are required. Thrusters must be developed for the Integrated LF_2/LH_2 attitude control subsystems.
Integrated Attitude Control System	Components comprising these systems will require extended lifetimes over existing candidate equivalents.

3.2.3 Storable Spacecraft (N_2O_4/50-50) (C)

(C) Since there are several large storable propellant vehicles in use at this time (Agena, Titan, Apollo Service Module, Apollo Lunar Module), there exist a number of storable components which were examined in this study. The conclusions are summarized in Table 3-6.

Table 3-6

SUMMARY OF COMPONENT AVAILABILITY FOR THE STORABLE SPACECRAFT (C)

(CONFIDENTIAL)

Component Class	General Conclusions
Liquid Valves	Suitable components are available with modifications. The ball valves should have movable seats or easily replaced cartridges.
Vent and Relief Valves	Suitable components are available with modifications.
Vent Disconnects	Suitable components are available.
Fill and Drain Disconnects	Suitable components are available.
Regulators	Suitable components are available with modifications. Leakages need improvement.
Pressurization Valves	Suitable components are available with modifications. Lower leakages needed.
Pressure Switches	Suitable components are available.
Pressure Transducers	Suitable components are available.
Check Valves	Suitable components are available with modifications. The leakages are generally too high.
Propellant Utilization	Vehicle would benefit from improved accuracies.
Attitude Control Thrusters	Thrusters with extended lifetimes are required.
Integrated Attitude Control	Liquid pumps and check valves need lifetime extensions.

3.3 ACCESSIBILITY STUDIES (U)

(U) An important activity was the evaluation of the component replacement requirements and the overall effect on the probability of failure (reliability) of the various subsystems. These investigations reflected significantly upon the predictability of the subsystems.

(U) The term "predictability" relates to the probability that a subsystem or component will conform to requirements over a given period of time. This term is used to indicate not only "reliability," but also the effects of replacement of components as a result of "wearout."

(U) There exists two probabilities of failure that are considerations in reusable systems:

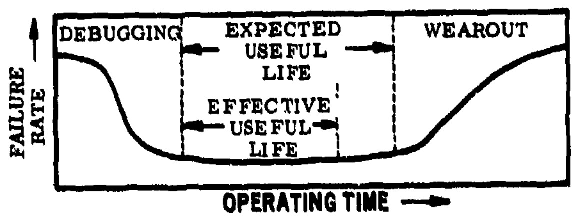
- The probability of failure per flight, which is a constant for all flights, if constant failure rates for the components may be assumed.
- The probability of failure in "N" number of flights, which does not relate to the probability of failure per flight, but is an excellent indicator for the comparison of reusable subsystems.

(U) The failure rate vs. operating time curve shown in Figure 3-3 provides the basis for reliability and lifetime considerations. In order for constant failure rates to be used, the flat portion of the curve must be the operating range of the component lifetimes. Almost no information exists on the "wearout" region with regard to the failure rates, and the prediction methods are beyond the scope of generally usable methods. Therefore, constant failure rates and exponentially distributed failures were accepted after an examination of the applicability of this approach.

(U) In order to assure that the components are operating in the effective useful life region, either component lifetime data are required (which is practically non-existent or the lifetimes must be estimated from known failure rate data (reliability data). If it is assumed that existing failure rate data are reasonably good, an estimate of this minimum wearout-failure-free life can be made for any degree of statistical confidence by utilizing the pure-chance chi-square (χ^2) estimator, given by the relationship presented in Figure 3-3.

(U) The System Effectiveness Tradeoff Analysis II (SETA II) computer program is a basic systems analysis and reliability tool for evaluating alternate designs, determining redundancy requirements, and evaluating the necessity of component replacement based on lifetime and the results of these replacements.

- COMPONENT LIFE



- MEAN TIME TO FAILURE (MTTF)
- MEAN TIME BETWEEN FAILURES (MTBF)
- BASIC FAILURE RATE

$$F.R. = \frac{1}{MTTF} \qquad F.R. = \frac{1}{MTBF}$$

- EXPONENTIALLY DISTRIBUTED FAILURES

$$F(t) = \frac{1}{m} \cdot e^{-t/m}$$

- THE MINIMUM WEAROUT FAILURE FREE PERIOD

$$M_L = \frac{2M}{\chi^2_{\alpha}(2n+2)}$$

M_L = THE LOWER LIMIT OF THE MEAN WEAROUT DISTRIBUTION

M = MEAN LIFE

χ^2 = THE PURE-CHANCE CHI-SQUARE NUMBER

Figure 3-3 Predictability Determinants (U)

(U) The SETA II program was used in several steps to evaluate all the subsystems under consideration for the three vehicles. The first step was to examine the systems with regard to the effects of redundancies of the components. The program performs this in a highly satisfactory manner, allowing by inspection the effects of the redundancy of each of the components of the system on probability of failure and replacement. From this examination, redundancies were selected based upon improvement, practicality, etc.

(U) The SETA II program was then used to determine the probabilities of failure per flight, and the probability of failure in "N" flights, as a function of the number of flights.

(U) Typical results selected at random are shown in Table 3-7. It should be noted that the multiple flights are affected by replacements, which hinders direct comparison of the numbers in tabular form. The effect of mission time, as shown by Missions I and II, is apparent. As may be seen, pressurization subsystems have high probabilities of failure and non-optimal redundancies may have to be standard practices.

Table 3-7

TYPICAL PROBABILITIES OF FAILURE (U)
(CONFIDENTIAL)

Vehicle	Mission	Subsystem	Probability of Failure Per Flight	Probability of Failure η Flights	Number of Flights η
Space Shuttle	I	Fill, Drain, and Feed	0.002646	0.2327	100
		Pressurization (GHe/GH_2-Mod)	0.01425	0.7835	100
		Pressurization (Auto Mod)	0.01453	0.791	100
	II	Fill, Drain, and Feed	0.0823	0.5739*	50
		Pressurization (GHe/GH_2-Mod)	0.04696	0.469**	50
		Pressurization (Auto Mod)	0.0539	0.6423*	50
FDL-5 LF_2/LH_2	III	Fill, Drain, and Feed	0.002014	0.058689	30
		Pressurization	0.002347	0.08439	30
	IV	Fill, Drain, and Feed	0.001172	0.1106	100
		Pressurization	0.001450	0.17317	100
FDL-5 N_2O_4/50-50	III	Fill, Drain, and Feed	0.001185	0.03496	30
		Pressurization	0.00124	0.0452	30
	V	Fill, Drain, and Feed	0.004775	0.0467	10
		Pressurization	0.006197	0.0842	10

*Values affected by replacements.

(U) The Systems Evaluation and Tradeoff Analysis computer program was modified to include a capability for estimating the component lifetimes when these estimates were not supplied to the program. As stated before, if it is assumed that the failure rate data (reliability data) are fairly accurate, then the minimum lifetimes can be estimated with a fair degree of accuracy. In these investigations, it was assumed that the confidence level should be 0.99. These lifetimes appear to be fairly consistent with the state-of-the-art and suppliers' estimates of the lifetimes of their components.

(U) At the end of the lifetime of each component, it was shown to be "replaced," and mission-phased plots were used to indicate the time of each required replacement.

3.4 SUBSYSTEM TRADEOFFS (U)

(U) The subsystem tradeoff evaluations were performed by displaying the various advantages and disadvantages of the subsystems in order that selections could be made. Considerable use was made of the SETA II outputs, which provided information on the number of component replacements and the relative probabilities of failure.

3.4.1 Reusable Launch Vehicle (U)

(U) The Reusable Launch Vehicle was given considerable attention in the tradeoff studies since it presented the largest number of possible subsystems.

Engine Operational Mode (U)

(C) The orbital maneuvers of the Space Shuttle vehicle require considerable propellant. LO_2/LH_2 propellant from the main tanks, or a separate tank for orbit maneuvering and deorbit, must be utilized. A major consideration in the study was the utilization of one (or possibly two) of the 350,000-lb-thrust engines for orbital maneuvering.

(U) The mode of operation of the engine has considerable impact upon the propulsion subsystems. The operation of the engine at approximately 10 percent thrust requires an engine cooldown and an operation in the normal pumped mode. If it is possible to operate the engine in a non-pumped idle mode (i.e., a pressure-fed engine operation), engine cooldown and propellant conditioning may be assumed to be unnecessary.

Table 3-8

LO_2/LH_2 ENGINE OPERATIONAL MODE, EFFECT ON PROPELLANT REQUIREMENTS (C)

(CONFIDENTIAL)

Cperational Mode	I_{sp}	Mission	Cool-down Propellant	Orbital ΔV Propellant	Total Propellant
Low Thrust (10%)	456	I	8,550	8,290	16,870
		II	10,260	6,770	17,030
Non-pumped Idle Mode (1% thrust)	440	I	Neg	8,600	8,600
		II	Neg	7,015	7,015
Non-pumped Idle start with Low Thrust Operation	440	I	(Must utilize 8550)	8,600	8,600
	456	II	(Must utilize 10,260)	7,015	7,015

(U) As may be seen above in Table 3-8, there is considerable weight saving in using the idle mode to eliminate cooldown requirements. Also, there is considerably less complexity in line cooling, propellant conditioning, etc.

(U) As shown in this study, and this is true for larger vehicles also, the idle mode start is not required, because if it is assumed that the same quantity of cooldown propellant must pass through the engine before low thrust is initiated, the velocity propellant is less than the cooldown propellant and the mode is not applicable.

(U) One disadvantage of the non-pumped idle mode discussed earlier is that pressurized engine bleed is not available.

(U) An alternative to these operational modes is to utilize a secondary propulsion system, such as a large integrated attitude control subsystem.

Summary of Selected Subsystems (U)

(U) A summary of the more important tradeoff results is as follows:

a. Pressurization Subsystem (C)

(1) Prepressurization of the tanks prior to liftoff from a ground supply and subsequent pressurization during ascent of the LH_2 tanks with GH_2 engine bleed and pressurization of the LO_2 tanks with GO_2 engine bleed.

(2) If the low thrust mode of engine operation is used for subsequent maneuvers, the autogeneous pressurization system, operating entirely from engine bleed is selected. OR: If the idle mode of engine operation, or a secondary propulsion subsystem is used, the pressurization must be provided from a pumped liquid to gas conversion subsystem (which operates much in the same manner as an integrated attitude control conversion subsystem).

b. Thermal Protection Subsystem (U)

(1) Ascent tanks insulated with foam type insulation

(2) Orbital transfer, maneuver and retro tanks insulated with multilayer insulation

(3) Multilayer insulation purged during reentry and landing

(4) Feedlines vacuum jacketed with the inclusion of multilayer insulation.

c. Propellant Utilization (U): A capacitance probe system was selected.

d. Attitude Control Subsystem (U): An integrated oxygen/hydrogen attitude control subsystem was selected.

3.4.2 Cryogenic Spacecraft (LF_2/LH_2) (C)

(C) The tradeoffs in the cryogenic spacecraft considered the refurbishment problems associated with fluorine subsystems. Some of the more significant conclusions are presented below:

Pressurization (U)

(C) The "instant start" method of pressurization was selected.

Thermal Protection of the Fluorine Tanks (C)

(C) Vacuum jacketing of the fluorine tanks was considered feasible, since the tanks are relatively small.

Attitude Control Subsystem (U)

(C) A separate N_2O_4/50-50 subsystem was selected considering the problems associated with replacement of components in an integrated LF_2/LH_2 attitude control subsystem.

3.4.3 Storable Spacecraft (N_2O_4/50-50) (C)

(C) The most important conclusion regarding the Storable Spacecraft Subsystems related to the propellant utilization subsystem and the attitude control subsystem. The selected propellant utilization subsystem was the use of a flowmeter. This appeared to be very feasible in the type of propulsion subsystem being proposed. The attitude control subsystem recommended was an integrated N_2O_4/50-50 subsystem.

Section 4
ADVANCED TECHNOLOGY RECOMMENDATIONS (U)

(U) Task 7, Advanced Technology, translated the reusable propulsion systems technology and component requirements derived throughout the study into recommendations for specific exploratory development programs. These programs are limited in scope to exploratory development and in subject matter to those portions of the propulsion system exclusive of the main engine (engine development is in progress under the AFRPL Advanced Development Programs). The recommended programs will make available to the reusable-vehicle development effort the critical technologies and components that pace the development of the vehicles.

4.1 ADVANCED TECHNOLOGY PROGRAMS (U)

(U) Advanced technology programs are construed to be those that explore completely new fields of technology (e.g., autogenous pressurization) or hitherto underdeveloped aspects of a relatively well explored field (e.g., thermal protection of reusable cryogenic vehicle tankage).

(U) The 11 programs listed in Table 4-1 include technologies related exclusively to the problems of reusable vehicles, such as leakage detection and the replacement of components, as well as technologies common to both expendable and reusable space vehicles (e.g., vent-free ground hold of oxidizers).

(U) The schedules and costs shown for these recommended programs are rough-order-of-magnitude estimates only. The actual schedules and costs will depend on such factors as the detailed statement of work, the amount of existing test apparatus available, and the number and type of analytical tools already developed by the contractor.

Table 4-1

ADVANCED TECHNOLOGY PROGRAMS (U)
(CONFIDENTIAL)

Program	Schedule (Mo)	Estimated Funding Requirement ($1000)
Idle Mode Vs Low-Thrust Pumped Mode for Orbital Maneuvers	9	150 + Engine Cont.
Autogenous Pressurization Vs Prepressurization	12	200 + Engine Cont.
LO_2/LH_2 Integrated Attitude Control Systems	24	750
Reducing Residual and Trapped Propellants	12	250
Liquid Sealing of Valves and Feed-Throughs	12	150
Leakage Detection Techniques for Reusable Propulsion Systems	9	250
Insulation System for Reusable – Vehicle Cryogenic Tanks	18	600
Replacement of Brazed and Welded Connections	9	200
Fracture Mechanics in Liquid Propellant Tankage	18	200
Surface Tension Characteristics of Liquid Propellants	9	150
Ground-Hold Vent Free Oxidizer System	12	300

4.2 ENGINEERING DEVELOPMENT (U)

(U) Engineering development programs are considered to be those in which an existing technology or design concept has been extended to meet the requirements of a particular reusable-vehicle application. These are presented in Table 4-2.

(U) The schedules and costs quoted for these programs are rough-order-of-magnitude estimates.

4.3 GENERAL PROGRAMS (U)

(U) The "general" programs are those which could not be identified as distinct technology programs, but which serve to provide considerable input into the reusable transportation system development. These are presented in Table 4-3.

4.4 RANKING OF THE SELECTED PROGRAMS (U)

(U) A matrix approach was used to evaluate the relative priority among the recommended programs. Criteria used were:

- The extent to which a program resolves a pacing element of technology
- The extent to which a program evaluates a long-leadtime tradeoff among major design alternatives
- The influence that the selected program will have on any concurrent effort in the AFRPL-sponsored engine Advanced Development Programs (ADPs).

(U) Note that, although some of these criteria duplicate the criteria for justification of programs, the emphasis in this analysis was on relative urgency rather than relative merit.

(U) These criteria were applied against the candidate programs for each of the three reference vehicles, using a simple rating scale (major, significant, minor) to make the evaluation. By assigning numerical values to these ratings, total scores and relative rankings were determined.

Table 4-2

ENGINEERING DEVELOPMENT PROGRAMS (U)
(CONFIDENTIAL)

Program	Schedule (Mo)	Funding ($1000)
Minimum-Impulse-Bit ACS Thruster	24	600
LO_2/LH_2 Thrusters	24	1,000
Vacuum-Jacketed Aluminum Lines for Cryogenic Feed Systems	12	150
Surface Tension Devices for ACS Propellant Orientation	18	250
Extended-Life Positive Expulsion Bellows	12	100
Structural Analysis and Optimization Program for Irregularly Shaped Propellant Tanks	9	100
Check Valve for LF_2 Service	12	200

Table 4-3

GENERAL PROGRAMS (U)
(CONFIDENTIAL)

Program	Schedule (Mo)	Estimated Funding Requirements ($1000)
Central Reusable Component Data Files	Continuous	50,000 + Annual Maintenance Costs
Propellant Specifications – Propellant and Gas Purity Cost Tradeoff	12	75
Contamination Data Compilation and Evaluations	18	150

(U) Using the ranking method just described, the relative priority analysis for the 11 advanced technology programs is shown in Table 4-4. The highest ranking programs are characterized by their major impact on the long-lead technology problems and design alternatives associated with all three reference vehicles.

(U) The ranking analysis for the seven engineering development programs is shown in Table 4-5. Note that several of these programs involve key design alternatives connected with attitude control system concepts for reusable vehicles, such as:

- Integrated ACS (main-tank fed) vs separate system
- Surface tension orientation vs positive expulsion for the separate system.

(U) As with the advanced-technology programs, the relative priority does not imply the relative merit of these programs.

(U) The "general" programs were judged to be of approximately equal priority.

Table 4-4

PRIORITY RANKING – ADVANCED TECHNOLOGY PROGRAMS (U)
(CONFIDENTIAL)

Program	1-1/2 Stage VTOHL			Cryogenic FDL-5			Storable FDL-5				
	Pacing Technology Problem	Key Tradeoff	Project 2 ADP Influence	Pacing Technology Problem	Key Tradeoff	Project 3 ADP Influence	Pacing Technology Problem	Key Tradeoff	Project 1 ADP Influence	TOTAL	Rank
Idle Mode vs Low Thrust		3	3		3	3				12	1
Oxygen/Hydrogen Integrated Attitude Control System		3			3			3		9	2
Leakage Detection for Reusable Vehicles	3			3			3			9	2
Cryogenic Insulation, Reusable Cryogenic Tanks	3			3			3			9	2
Autogenous Pressurization vs Prepressurization		2	2		2	2				8	3
Replacement of Brazed/Welded Connections	2			2			2			6	4
Fracture Mechanics	2			2			2			6	4
Surface Tension Characteristics	2			2			2			6	4
Liquid Sealing of Valves	2			2			2			6	4
Ground Vent-Free Oxidizer System				1			3			4	5
Reducing Residual Propellants	3									3	6

Table 4-5

PRIORITY RANKING – ENGINEERING DEVELOPMENT PROGRAMS (U)
(CONFIDENTIAL)

Program	1-1/2 Stage VTOHL			Storable FDL-5			Cryogenic FDL-5				
	Pacing Technology Problem	Key Tradeoff	Project 2 ADP Influence	Pacing Technology Problem	Key Tradeoff	Project 1 ADP Influence	Pacing Technology Problem	Key Tradeoff	Project 3 ADP Influence	TOTAL	Rank
Minimum-Impulse-Bit ACS Thruster	3			3			3			9	1
Oxygen/Hydrogen Integrated ACS Thruster		3			3			3		9	1
Surface Tension Devices for ACS	2			2			2			6	2
Extended-Life Bellows	2			2			2			6	2
Vacuum Jacketed Aluminum Lines	3						1			4	3
Structural Analysis of Irregular Tanks	1			1			1			3	4
LF_2 Check Valve							3			3	4

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13\. ABSTRACT

ABSTRACT (U)

(U) Volume I presents a summary of the entire study. The objective of each of the seven tasks is presented. The baseline vehicles and missions selected in Task 1 – Selection of Vehicles and Missions, are briefly described. The major activities performed under Task 2 – Vehicle Design Extensions and Subsystem Analysis, are reviewed. Special problem analyses performed under Task 3 – Extension of Subsystem Analyses are discussed. The approach and results summary are presented for Task 4 – Determination of Subsystem Requirements. The conclusions are reviewed for the principal task of the study, Task 5 – Reusability of Existing Hardware. Summary conclusions are presented regarding hardware availability. The subsystem approaches selected under Task 6 – Subsystem Tradeoff Evaluations, are discussed. A summary listing and discussion is presented of the selected advanced technology, engineering development, and general programs resulting from Task 7 – Advanced Technology Recommendations.

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Propulsion Subsystem Requirements						
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Reusable Space Vehicles						
Launch Vehicles						
Space Missions						
Reusable Vehicle Requirements						
Reusable Tankage, Insulation, Components, etc.						
Subsystem Tradeoffs (Reusable)						
Systems Effectiveness Analysis						
Advanced Technology for Reusable Vehicles						

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